RECONFIGURABLE PHOTONIC BANDGAP DEVICE WITH MEMS FEATURES

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Abstract

We report on our design and fabrication of a semiconductor based photonic bandgap nano-membrane device with MEMS features. This device could be used as a basic building block for a reconfigurable optoelectronic integrated circuit that can be reprogrammed for many different functionalities.

Introduction

It is highly desirable for the Army's future combat systems to have miniature photonic integrated circuits (PICs) to perform many different electronic and optoelectronic signal processing tasks for different type of military electronic systems such as communication, radar, sensors, imaging, etc. Rather than designing and producing a large numbers of different specialized PICs (at great cost), one would like a single, mass-produced PIC device that can be reconfigured for a variety of desired functions as they are needed. If there were a "universal" waveguide structure that could actively appear/disappear and change between different types of devices on a common platform, one could build such a PIC on that platform. Photonic bandgap (PBG) material has a perfect crystal lattice structure that disallows the propagation of light of certain wavelengths. When a defect line is created on a photonic crystal structure, it can be used as an optical waveguide. Varying the physical dimensions of the defect line can change the dispersion properties of the waveguide. Therefore, photonic crystals could be used as the platform of the reconfigurable PIC if one could actively generate/cancel defect lines as desired. Photonic crystal waveguides can further condense the light propagation so that the devices can be reduced to sub-micrometer scale, which gives additional advantages for small size/weight and low power consumption. In this work, we combine a PBG platform with a MEMS feature to build such a reconfigurable device. Since the MEMS-activated PBG waveguide can appear and disappear from the PBG platform through control by electronics and software, this type of integrated circuit has also an advantage against counterfeiting and reverse engineering, so it may be used for secured secret codes processing.

Design and Simulation

This PBG device is designed for III-V semiconductor material. Since coupling light in and out of PBG waveguide may suffer great insertion loss, it is very desirable to integrate the light source and detector into the PIC. III-V semiconductors allow the monolithic integration of these active devices with other passive waveguides. As shown in Fig. 1, the device has a top photonic crystal membrane layer. This photonic crystal forms a PBG that disallows light at the operating wavelength to propagate in any in-plane direction of the membrane. Below that, a separate suspended bridge layer acting as an active MEMS feature can insert a line of posts into the photonic crystal holes to create a defect line and form a waveguide. We have a second design that replaces the suspended bridge with a

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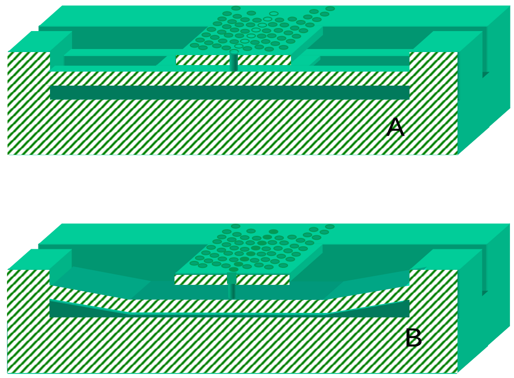

Fig. 1 Reconfigurable PBG-MEMS Device. A) Waveguide generated by a line of inserted posts into the PBG holes; B) The posted are removed.

cantilever actuator to hold the posts. This MEMS feature can generate/cancel a section of the waveguide in the PBG platform, or it can change the dispersion of the waveguide. Therefore, the same structure can be used as different types of devices such as switches, modulators, time delay lines, etc.

In order to reduce the difficulties of fabrication of the PBG/MEMS, we have searched and simulated many PBG structures such as circular holes, triangular holes and hexagonal holes to find one that has reasonable large PBG holes with a reasonably large band-gap. Finally, we have selected a PBG structure of hexagon holes in a triangular lattice as shown in Fig 2. Fig. 2 also shows the results of a 2D plane wave expansion calculation (using software from EM-Photonics) for a PBG structure composed of hexagonal holes in a triangular lattice using the refractive index of GaAs, where we can find two band-gaps for the TE mode and one band-gap for the TM mode in the displayed range. In this case, the first TM mode (green) band gap is overlapped with the second bandgap of the TE mode (red). We chose to use this overlapped band-gap of the first TM mode and the second TE mode. For an operating light with 1550 nm wavelength, it gives relatively large holes (~1 μm) so that in fabrication, it is easier to get a post insert into the holes. But the wall between the holes is only 130 nm thick. A simple 1-D planar waveguide calculation has also been done to determine the membrane thickness. Two sizes were chosen. One is about 200 nm which gives a tight single optical mode confinement. The second thickness is about 60

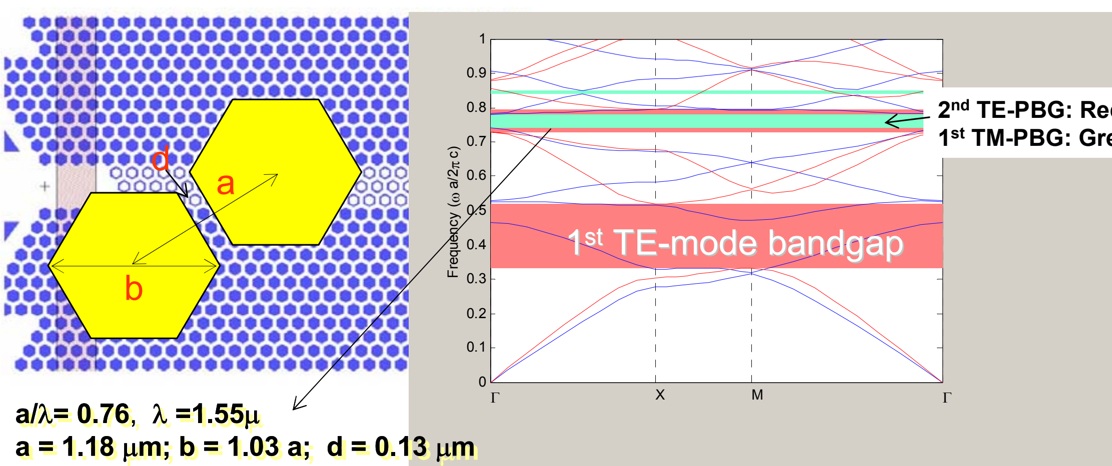

Fig.2. Hexagon holes in a triangular lattice structure (left). Two enlarged hexagons are insert on top. a is the lattice constant, b is width and d is the gap distance between the two hexagons. The calculated photonic band gaps for TE and TM modes are shown on the right side.

nm which results in an evanescent over-mode propagation.

Fabrication

This device is fabricated on GaAs/Al_{x1}GaAs/Al_{x2}GaAs/GaAs-substrate epilayers grown by molecular beam epitaxy (MBE). The first step is to define the PBG structure and other linked devices structure on the top GaAs membrane layer by e-beam lithography and inductively coupled plasma (ICP) reactive ion etching. For e-beam lithography, we used Zep 520 as the E-beam resist, 100KV e-beam energy with 150-190 mC/cm dose, 50 nm spot size and 40 nm resolution. The ICP etch recipe was: Cl: 2.5 sccm; BCl3:12.5sccm; and Ar:10 sccm., at 3 mT pressure, RF1 power of 100W and RF2 power of 500W. The MEMS posts are also defined by etching a ring shape instead of a circle in the PBG structure. Fig. 3 shows a SEM picture of one of the PBG-MEMS device structures after the first step ICP etching. This etch is about 300 nm deep which goes through the top GaAs layer. The fist step defines not only the PBG membrane structure with a line of MEMS post, but also the regular input and out put ridge waveguides as well as the cantilever and the electric contact area. The second step is to use regular photolithography to open thin lines to define the second suspension bridge or cantilever made by the Al_{x1}GaAs ($x1 \sim 0.45$) layer under the GaAs membrane. Dilute buffered HF is used to selectively etch a deep trench through the Al_{x1}GaAs layer. Once the HF reaches the high Al concentration Al_{x2}GaAs sacrificial layer underneath, fast undercutting takes place to remove this layer under the bridge as shown in Fig 4. The third step is a critically controlled chemical etch to separate the GaAs membrane layer from the Al_{x1}GaAs suspension bridge/cantilever layer with attached MEMS posts. As shown in Fig. 5, this HF etch is just enough to completely under-cut below the PBG walls and separate

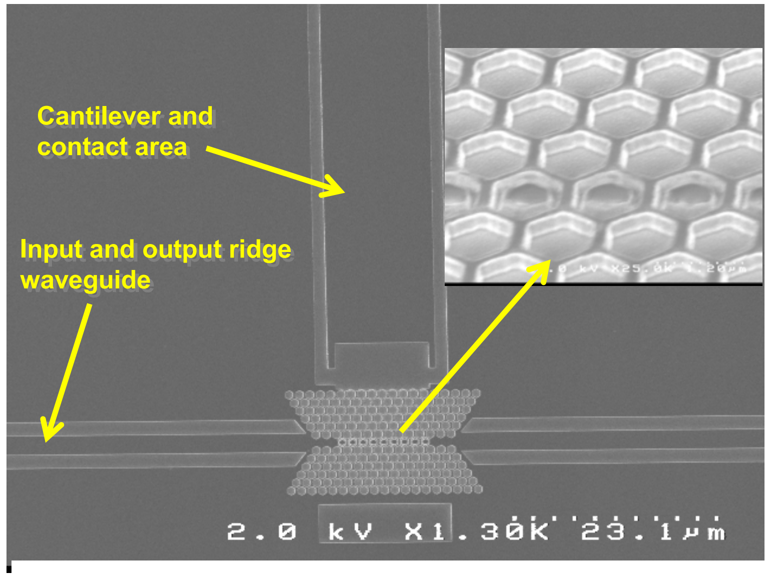

Fig. 3. SEM picture of the device structure after the first step ICP etch.

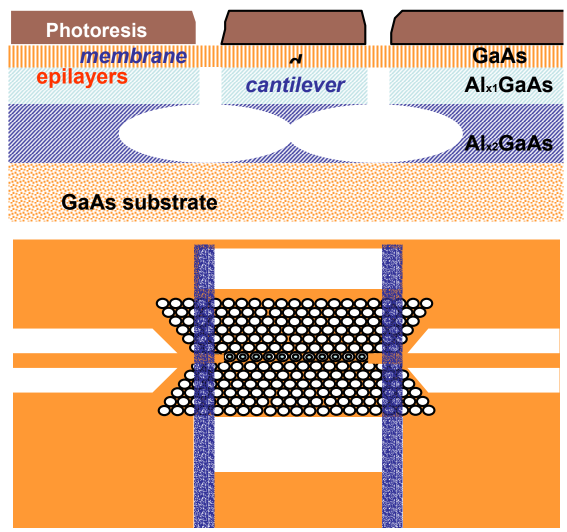

Fig. 4. Schematic illustration of wet chemical under-cut etching of the sacrificial layer to form the cantilever. Top part: cross-section; bottom part: top view.

membrane layer, but the under-cut below the post is not complete so that the post is still attached to the cantilever like a mushroom. Fig. 6 shows some of the SEM pictures of a PBG-MEMS device structure after the third step chemical etching. We have obtained 60 nm thick membrane layer with a PBG structure having 130 nm thick walls between the hexagonal holes with mushroom shaped

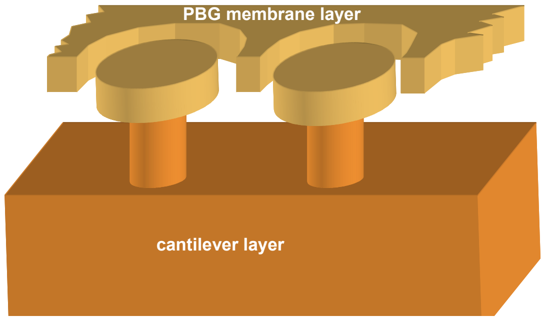

Fig. 5. Schematic illustration of wet chemical under-cut etching to release the membrane layer from cantilever.

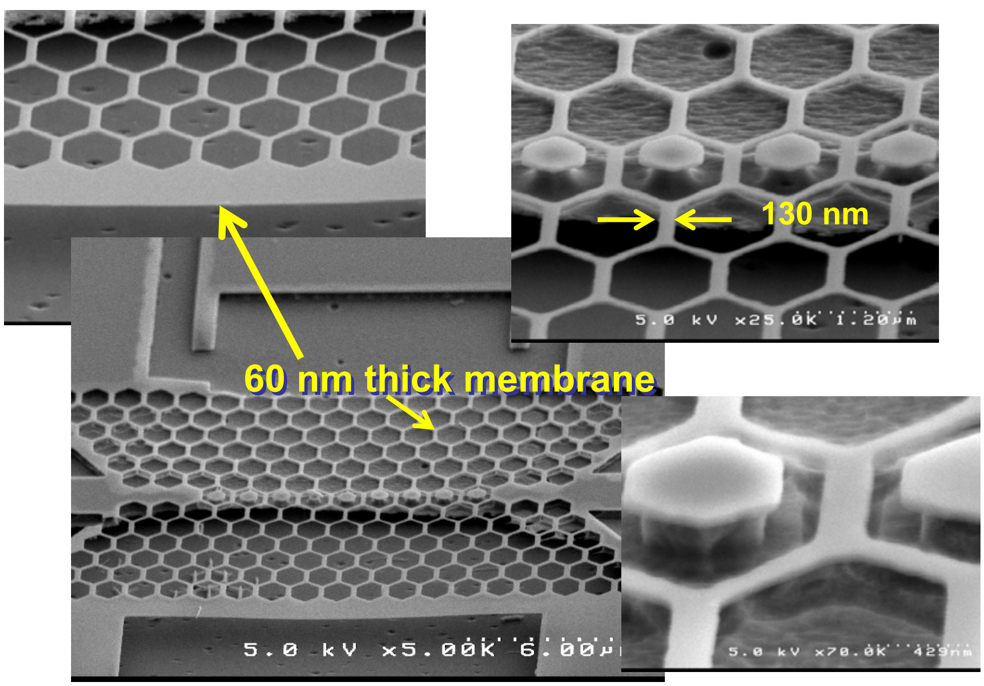

Fig. 6. SEM pictures of the PBG-MEMS device structure after the third step wet chemical under-cut etch.

posts inserted into the holes from the cantilever layer below. The final step is to produce a metallic contact for the suspension bridge by ion-implantation for electrical isolation and metal deposition. An electrical bias between this metallic contact and the n-type substrate induces a Coulomb attraction between them that removes the inserted posts from the PBG holes in the membrane.

Conclusion

We have designed a semiconductor reconfigurable photonic band-gap waveguide device with MEMS features that can activate the waveguide into different functionalities such as switch, modulator, or delay line. We have developed a fabrication technique for such a device. For the first time, we have achieved the fabrication of a 60 nm thick membrane layer with a PBG structure having 130 nm thick walls between the hexagonal holes with mushroom shaped posts inserted into the holes from the cantilever layer below. We are fine tuning each of these processing steps toward the fabrication of a workable device.